



Hoary Bat (*Lasiurus cinereus*) ecology and conservation through the lens of the full annual cycle

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Abstract

The Hoary Bat (*Lasiurus cinereus*) is the most frequently reported bat killed at North American wind energy facilities, driving the United States and Canada to consider regulatory protections for the species. The Hoary Bat is a widely distributed, long-distance migratory bat, but gaps remain about the species' ecology to inform best practices for conservation and management. We synthesize information on Hoary Bat ecology in the context of the full annual cycle, with specific attention paid to the species' interactions with wind turbines. Hoary bats generally hibernate through winter, especially at lower latitudes and in coastal areas. In spring, hoary bats migrate from winter to summer habitat. Spring is also characterized by pregnancy for females; pups are born in summer. Migration to overwintering sites and mating both occur in late summer and autumn, with adults searching for mating opportunities over large spatial expanses. Late summer and early autumn coincide with a peak in wind turbine fatalities. This seasonality in fatality events provides an opportunity to concentrate conservation efforts to reduce collision risk. While various fatality minimization strategies are under development, curtailment is currently the most effective strategy available. Systematic sampling at wind energy facilities for turbine-related fatalities, acoustic and genetic sampling, and better data sharing offer opportunities to better estimate the species' population status and trends. While questions remain, enough information exists to make informed decisions to reduce the impact of wind turbines on hoary bats as scientists pursue research to better inform future management decisions.

Keywords aeroecology, bat conservation, migration, species risk assessment, wind energy mitigation

Ecología y conservación del murciélago canoso desde una perspectiva del ciclo anual completo

Resumen

El murciélago canoso (*Lasiurus cinereus*) es la especie de murciélago que se reporta con mayor frecuencia como muerta en instalaciones de energía eólica en Norteamérica, lo que ha llevado a Estados Unidos y Canadá a considerar protecciones regulatorias para la especie. El murciélago es ampliamente distribuido y migrador de larga distancia; sin embargo, aún existen vacíos de información sobre su ecología que limitan el desarrollo de mejores prácticas para su conservación y manejo. Sintetizamos la información disponible sobre la ecología del murciélago canoso a lo largo de su ciclo anual completo, con especial énfasis en su interacción con turbinas eólicas. Generalmente, estos murciélagos hibernan durante el invierno, especialmente en latitudes más bajas y en zonas costeras. En primavera, los murciélagos canosos migran desde sus áreas de invernada hacia sus hábitats de verano. En las hembras, esta estación también se caracteriza por la gestación y el desplazamiento hacia sitios de crianza; las crías nacen en verano. La migración hacia los sitios de invernada y el apareamiento ocurren a finales del verano y en otoño, cuando los adultos buscan oportunidades reproductivas en amplias áreas geográficas. Este periodo coincide con un pico en la mortalidad asociada a turbinas eólicas. Esta estacionalidad en los eventos de mortalidad brinda una oportunidad para concentrar los esfuerzos de conservación en la reducción del riesgo de colisión. Aunque

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diversas estrategias para minimizar la mortalidad están en desarrollo, la reducción operativa de turbinas es actualmente la más efectiva. El muestreo sistemático en instalaciones eólicas, junto con el uso de herramientas acústicas y genéticas, así como una mejor colaboración en el intercambio de datos, ofrecen oportunidades para estimar con mayor precisión el estado y las tendencias poblacionales de la especie. Si bien aún quedan preguntas por resolver, existe suficiente información para tomar decisiones informadas que reduzcan el impacto de las turbinas eólicas sobre el murciélago canoso, mientras la comunidad científica continúa generando conocimiento que permita mejorar las prácticas de manejo en el futuro.

Palabras clave aeroecología, conservación de murciélagos, evaluación del riesgo de la especie, migración, mitigación de la energía eólica

Species conservation can be improved by comprehensively assessing needs and challenges across the full annual cycle instead of using approaches that only focus on specific habitats and seasons, such as the breeding season (Marra et al. 2015). Conservation assessments that account for a full annual cycle are particularly relevant for long-distance migratory species that may encounter radically different environmental threats at different times of the year (Flockhart et al. 2015; Rushing et al. 2016; Grand et al. 2019). For example, waterfowl populations across North America stabilized following the establishment of mechanisms to create and maintain habitat across the full annual cycle—breeding, wintering, and migratory stopovers—along with the coordination of species-specific hunting regulations across political boundaries within flyways (Anderson et al. 2018). Hoary Bats (*Lasiurus cinereus*) are an ideal candidate for applying an annual cycle framework for species conservation because their ecology and behaviors differ markedly among the seasons, and they use long-distance movements to connect winter and summer habitats.

Hoary bats occur widely across North America (Gonzalez et al. 2016) and face multiple anthropogenic pressures, including reductions in insect prey, habitat degradation, exposure to environmental toxins, and direct mortality from wind turbines (O'Shea et al. 2016; Frick et al. 2017). Notably across the United States and Canada, Hoary Bats are the most frequently killed bat species at wind energy facilities (Zimmerling and Francis 2016; Renewable Energy Wildlife Institute [REWI] 2026). Fatalities at wind turbines are concentrated during late summer and autumn when hoary bats are migrating and mating, potentially leading to rapid population decline or extinction if not addressed (Frick et al. 2017; Friedenbergs and Frick 2021). Accordingly, in 2023, the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) determined that hoary bats met multiple criteria for listing as endangered under Canada's Species at Risk Act (criteria A2be + 3be + 4be and E as defined by IUCN 2012). The US Fish and Wildlife Service (USFWS) is expected to consider the species for protection under the Endangered Species Act in 2028 (USFWS 2024a). As a wide-ranging, open-air foraging insectivorous bat, hoary bats provide ecosystem services in the form of pest reduction (Maine and Boyles 2015; Frank 2024), so a rapid decline of this species could have economic consequences. The regulatory restrictions that accompany protection as a threatened or endangered species would likely have further economic consequences for industries, including timber and energy production. Although fundamental information on population size and growth rate is limited for this species, understanding of movement, habitat requirements, demography, and behavior is improving because of increased effort and advances in research technologies.

Our aim is to synthesize Hoary Bat ecology in the context of the annual cycle to gain a deeper understanding of how seasonal requirements (e.g., hibernating, migrating, maternity, and mating) may influence behavior, interactions with conspecifics, and movement in

ways that contribute to the primary conservation challenges for the species. We pay specific attention to Hoary Bat interactions with wind energy infrastructure because the research in this area is extensive and because of the disproportionate impact this stressor have on Hoary Bat population viability and wind energy production. By summarizing current knowledge and identifying knowledge gaps, we can contribute to cost-effective conservation planning and spur targeted research to stabilize populations before they decline further.

Ecological overview

Geographic range and habitat

Lasiurus cinereus (family Vespertilionidae, subgenus *Aeorestes*) is one of the most widely distributed bats in the Western Hemisphere, found from the boreal forest in Canada to Central America (Gonzalez et al. 2016; Fig. 1). This species was recently recognized as distinct from other hoary bats in the Western Hemisphere: *Lasiurus egregius* found in Panama and northern South America and *Lasiurus villosissimus* in South America (Díaz et al. 2023). In addition to its continental distribution, the Hoary Bat colonized the Hawaiian Islands around 1.34 million years ago (Pinzari et al. 2020). The 'ōpe'ape'a, or Hawaiian Hoary Bat (*Lasiurus semotus*), is now recognized as its own species and listed as endangered in Hawaii (35 FR 16047 16048; Pinzari et al. 2020). (Hereafter, we use "Hoary Bat" to refer specifically to *L. cinereus*.)

Hoary bats use a variety of habitat types to forage, commute, and roost, including deciduous and coniferous forests, grasslands, deserts, riparian corridors, croplands, and urban areas (Shump and Shump 1982). Given the large extent of their geographic range and annual movements, defining and identifying critical habitat for this species is difficult. Regardless, reliance of the Hoary Bat on open-air foraging and long-distance migratory movements makes aerial habitats, in addition to terrestrial features, important to the species (Chilson et al. 2012; Diehl 2013).

Hoary Bat roosts are ephemeral and less discrete than cavity roosts used by colonial species, making them less suitable for traditional roost-focused conservation strategies. Although characterization of roost sites is limited to a small number of studies and locations compared to other North American forest bats (Table 1), hoary bats are known to be solitary, tree-roosting obligates. While individuals have been found roosting on tree trunks (e.g., Clifton 2015; Yokoi 2024; Weller personal communication), in Spanish Moss (*Tillandsia usneoides*; Barbour and Davis 1969), shrubs (Marín et al. 2021), and other substrates (see Gruver 2002 for a list of less commonly reported roost sites), most roosts are in the tree canopy where individuals hang from branches. They regularly roost along forest edges and near roads (Loeb and O'Keefe 2011; Salganek et al. 2022). A systematic review of forest bat roost sites in the eastern temperate forest estimated that hoary bats occupy >93% of forests in this ecoregion, roosting

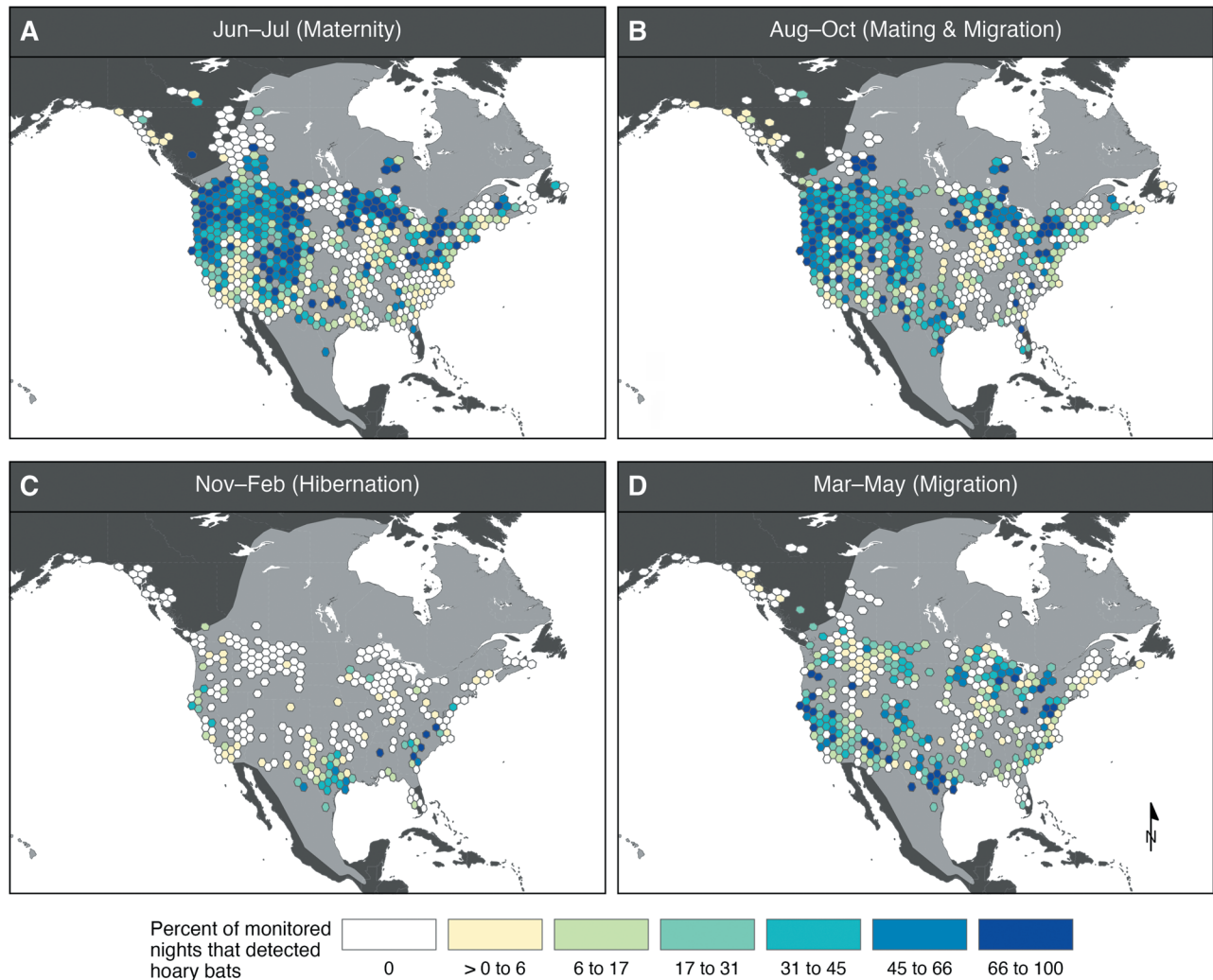


Fig. 1 Percentage of nights for which hoary bats were detected during echolocation monitoring surveys by season: A) maternity (June–July), B) mating and migration (August–October), C) hibernation (November–February), and D) migration (March–May). Detection data for hoary bats (*L. cinereus*) were drawn from 2 sources: the NABat Program provided 329,409 nightly survey records spanning North America (NABat [a], NABat [b]); and BatAMP surveys provided 204,661 unique nightly detection records not present in NABat (2001 to 2026; Ward and Weller 2026). The accepted Hoary Bat range is depicted in lighter gray.

primarily in the foliage of live deciduous trees (41.2%) and higher in the canopy relative to other species (mean roost height of 21.1 m; Drake et al. 2020). A study tracking 7 males and 1 non-breeding female near a wind energy project in Wyoming in the summer found that individuals selected forested edge habitat with sufficient canopy cover and proximity to water for roosting (Gruver 2002). Mothers with young select sites in trees with lower wind speeds, less canopy coverage at the exit side of the roost, and sheltered microclimates (Willis and Brigham 2005; Klug 2011).

Foraging and echolocation

Hoary bats are morphologically adapted to flight in open spaces (i.e., long narrow wings, low wing loading; Shump and Shump 1982; de la Cueva Salcedo et al. 1995; Menzel et al. 2005). They maneuver less than other species, flying in straight-line paths and using echolocation designed to detect prey at long distances. Hoary bats capture aerial insects while in flight, and their echolocation call characteristics are consistent with long-range detection of large-bodied prey (Barclay 1985). With longer-than-average commute distances compared to other insectivorous bats (Fenton 1997), Hoary Bat foraging habitats

include wetlands, riparian corridors, open areas, and edge or gap habitats in forested landscapes. While the diet of hoary bats has been described as being composed mostly of moths (Lepidoptera; e.g., Black 1972, 1974; Barclay 1985), they consume a wide variety of prey, including but not limited to beetles (Coleoptera), flies and mosquitoes (Diptera), wasps and ants (Hymenoptera), lacewings (Neuroptera), crickets and grasshoppers (Orthoptera), true bugs (Hemiptera), spiders (Araneae), and dragonflies (Odonata; Barclay 1985; Rolseth et al. 1994; Valdez and Cryan 2009; Reimer et al. 2010; Perlik et al. 2012; Valdez and Cryan 2013; Foo et al. 2017; Karevold 2021; Perea et al. 2024). Hoary bats are opportunistic foragers exploiting locally abundant prey, so diet composition varies regionally and temporally. For example, during spring migration in New Mexico, the predominance of moths in Hoary Bat diets corresponds to the timing of irruptions of cutworm (Noctuidae) and other moths (Valdez and Cryan 2009). Hoary Bat diets can also vary demographically due to differences in the energetic demands of males and females at different times of the year and because of differences in foraging abilities and habitats between juveniles and adults (Rolseth et al. 1994; de la Cueva Salcedo et al. 1995; Reimer et al. 2010).

Table 1 Hoary Bat roost site descriptions according to various studies.

Study	Location	Habitat	Season	Method	No. bats (m/f/j)	No. roosts (m/f/j)	Description of roost sites within and between trees
Constantine 1966	Iowa, United States	Trees in town	Summer	Visual survey, hand netting, and banding	20 (0/8/12)	24 (0/10/14)	In foliage of mainly American elm, but several other deciduous species
Barclay 1984	Manitoba, Canada	Deciduous forest and marsh	Spring to early autumn	Visual survey, harp trap, and banding	36 (9/11/15), 1 unknown	18 (not stated)	High in trees (8 to 12 m above ground), primarily in Green Ash (<i>Fraxinus</i> <i>pennsylvanicus</i>) near the end of a branch, occasionally in a clump of seeds
Gruver 2002	Wyoming, United States	Lodgepole pine and aspen	Summer	Radio-telemetry	8 (not stated)	17 (not stated)	Live lodgepole pine (taller and closer to water than random) and two <5 m shrubs
Sparks et al. 2005	Indiana, United States	Mixed forest, near international airport	Summer	Radio-telemetry	1 (0/0/1)	3 (0/0/3)	Foliage in 1 tree, unknown in others but always high in eastern cottonwood
Willis and Brigham 2005	Saskatchewan, Canada	Mixed forest	Summer	Radio-telemetry	25 (0/21/4)	32 (0/32/0) ^a	Foliage of white spruce trees, but did not find preference for taller trees
Perry and Thill 2007	Arkansas, United States	Mixed forest	Late-spring/ early summer	Radio-telemetry	9 (4/5/0)	12 (6/6/0)	Indicated preference for taller trees
Veilleux et al. 2009	New Hampshire, United States	Mixed forest	Summer	Radio-telemetry	1 (0/0/1)	6 (0/0/6)	Foliage near top of eastern hemlocks
Klug et al. 2012	Manitoba, Canada	Deciduous forest and marsh	Summer	Visual survey	Unknown	19 (0/19/0)	Foliage of 3 species of deciduous trees, but did not find preference for taller trees
Jorge et al. 2021	Florida, United States	Largely pine forest or plantation	Winter	Radio-telemetry	1 (not stated)	4 (not stated)	One in loblolly pine, 3 in water oak
Salganek et al. 2022	California, United States	Mixed forest	Autumn	Radio-telemetry and GPS	16 (16/0/0)	24 (24/0/0)	Found limited evidence of preference for taller trees

For each study, the location, habitat, season, and data collection method are included. Sample sizes for each study are also included, via the number of bats and number of roost sites, broken down by adult male (m), adult female (f), and juvenile (j) in cases where this is known.

^aLactating females and volant juveniles were all tracked to maternity roosts.

Hoary bats produce low-frequency (~17 to 30 kHz), high-intensity (~110 to 135 peSPL dB), frequency-modulated echolocation calls that propagate greater distances than calls of other North American bat species (Fenton and Bell 1981; Barclay et al. 1999; O'Farrell et al. 2000; Corcoran and Weller 2018) and are readily distinguishable from most other bat species in North America (Weller and Baldwin 2012; Starbuck et al. 2022). However, acoustic detection rates for hoary bats may be reduced because they often fly higher than other species (Menzel et al. 2005; Reimer et al. 2018), so Hoary Bat calls may be missed by ground-based detectors. Additionally, under certain conditions hoary bats use low-intensity echolocation (i.e., micro-calls), or do not echolocate at all, possibly to avoid eavesdropping by conspecifics (Corcoran and Weller 2018).

Social behavior

Although hoary bats are typically solitary, they exhibit some social behaviors associated with mating and swarming (Reyes and Szewczak 2022). Hoary bats are known to be aggressive, with various documented accounts of chasing during swarming events (Hall 1946 as cited in Cryan 2008; Ore 1950; Barclay 1984, 1985), and even fatal attacks by hoary bats on other bat species (Bishop 1947; Bell 1980; Krynnack and Riebe 2013; Brokaw et al. 2016; Wine et al. 2019). As with other species, aggression is likely in defense of resources, including access to mating and foraging opportunities (Shump and Shump 1982; Cryan and Brown 2007; Kerth 2008). While both sexes may exhibit antagonistic behaviors, males are most often implicated in records in which sex is known (Ore 1950; Reyes and Szewczak 2022).

The species also produces social calls, which are generally lower in frequency than their echolocation calls and therefore likely extend the distance over which individuals can communicate with conspecifics. Multiple functions of in-flight social calls have been proposed for bats more generally, including mate attraction, territoriality, and the attraction of conspecifics to roost sites (Belwood and Fullard 1984; Pfalzer and Kusch 2003; Chaverri et al. 2018). Distinct from echolocation, Hoary Bat social calls are lower frequency (mean 13 kHz), longer duration (mean 33 ms, range 12 to 100 ms; Reyes and Szewczak 2022), and up-sweeping in shape (mean end frequency 15 ms). These social calls may be underreported in conventional acoustic monitoring because the low-frequency and long-duration calls may be screened out as non-bat calls in some configurations of auto-identification software (Gorresen et al. 2017). It is unclear if the use of social calls changes seasonally, although studies have documented mostly male hoary bats producing and responding to social calls spring through autumn (Reyes and Szewczak 2022).

Hoary Bat annual cycle

Like many temperate-zone bats (Senior et al. 2005), hoary bats sexually segregate during much of the annual cycle and express sex-specific behaviors to meet their seasonal needs (Findley and Jones 1964; Cryan 2003). Reproductive effort also differs temporally between the sexes, with maximum energy expenditure by males during the late summer and autumn mating season and by females during gestation and pup rearing (late spring and summer; Gustafson 1979; Fig. 2). Hence, season-specific threats may impact the sexes differently throughout the annual cycle.

Winter hibernation season

Little is known about Hoary Bat movements, behavior, and vocalizations during the winter. Females of many bat species can store sperm through the winter until fertilization in the spring (Racey 1979). Hoary Bat reproduction aligns with that observed in other Vespertilionid bats: a delay between mating and gestation, with copulation generally occurring in the late summer and autumn but not resulting in pregnancy until spring (Wimsatt 1945; Cockrum 1955). Exact gestation duration is unknown, but females use torpor in winter and early spring to extend gestation to reduce fetal growth rate so that parturition will coincide with favorable weather conditions later in spring (Willis et al. 2006).

Extended bouts of torpor likely contribute to a large range of suitable wintering habitat for hoary bats, although reports of the species wintering in extremely cold climates (i.e., protracted periods below freezing) are rare (NABat[a]; NABat[b]; Ward and Weller 2025; Fig. 1). We are unaware of any documented locations where hoary bats roost in large numbers during the winter—possibly because there are none—further supporting a wide geographic distribution and solitary behavior during this season.

Museum records indicate that hoary bats winter mostly along the Pacific Coast, throughout Mexico, and in the south-central and eastern United States (Cryan 2003; Hayes et al. 2015), although additional data are needed to make comprehensive inferences about their winter range (Hayes et al. 2015). While occurrence records in winter are too limited to separate sexes in distribution models (Hayes et al. 2015), evidence suggests that some sexual segregation occurs even in winter in some regions. For instance, Cryan (2003) noted that winter records of hoary bats from Mexico were distinctly male-biased, whereas winter records from California had a balanced sex ratio.

During early winter, bats may make long-distance movements to wintering sites. However, mid- to late-winter movements are likely to be local. Where Hoary Bat behavior has been monitored during winter, they appear to be hibernating in their roost trees. For example, a Hoary Bat in central Mexico at an elevation of 3,286 m was torpid and inactive for 13 days in November (Marín et al. 2021). As another example, a male Hoary Bat wintering in northwestern California consistently used multi-day torpor bouts, including 4 bouts that were 18 days or longer; 1 of those 4 was a 40-day torpor bout centered on January (Weller et al. 2016). Nonetheless, a Hoary Bat in Florida was tracked to 4 roosts, indicating that movement and activity can occur during winter (Jorge et al. 2021). Such movements in winter may be attributed to seeking mates, feeding, drinking, or switching roost microclimates (Boyles et al. 2020).

Hoary Bat activity during winter (December to February) has also been confirmed with acoustic records as far north as south-central British Columbia (NABat[a]; NABat[b]; Ward and Weller 2025; Fig. 1). Winter activity of hoary bats has been regularly reported along the coastal plains of the southeastern United States (Grider et al. 2016; Anderson et al. 2022; Perea et al. 2024), throughout North Carolina (Parker et al. 2020), and in redwood forests in California (Andreozzi and Merenlender 2024). However, hoary bats were not detected during winter acoustic studies in Montana (Schwab and Mabee 2014) or southeastern Alberta (Lausen and Barclay 2006), 2 areas with colder and drier climates than those where the species has been reported to be active during this season (Fig. 1).

Some local winter movements of the species may be explained by metabolic needs. Hoary bats are not known to use thermally buffered roosts such as caves, buildings, or the interiors of trees during winter

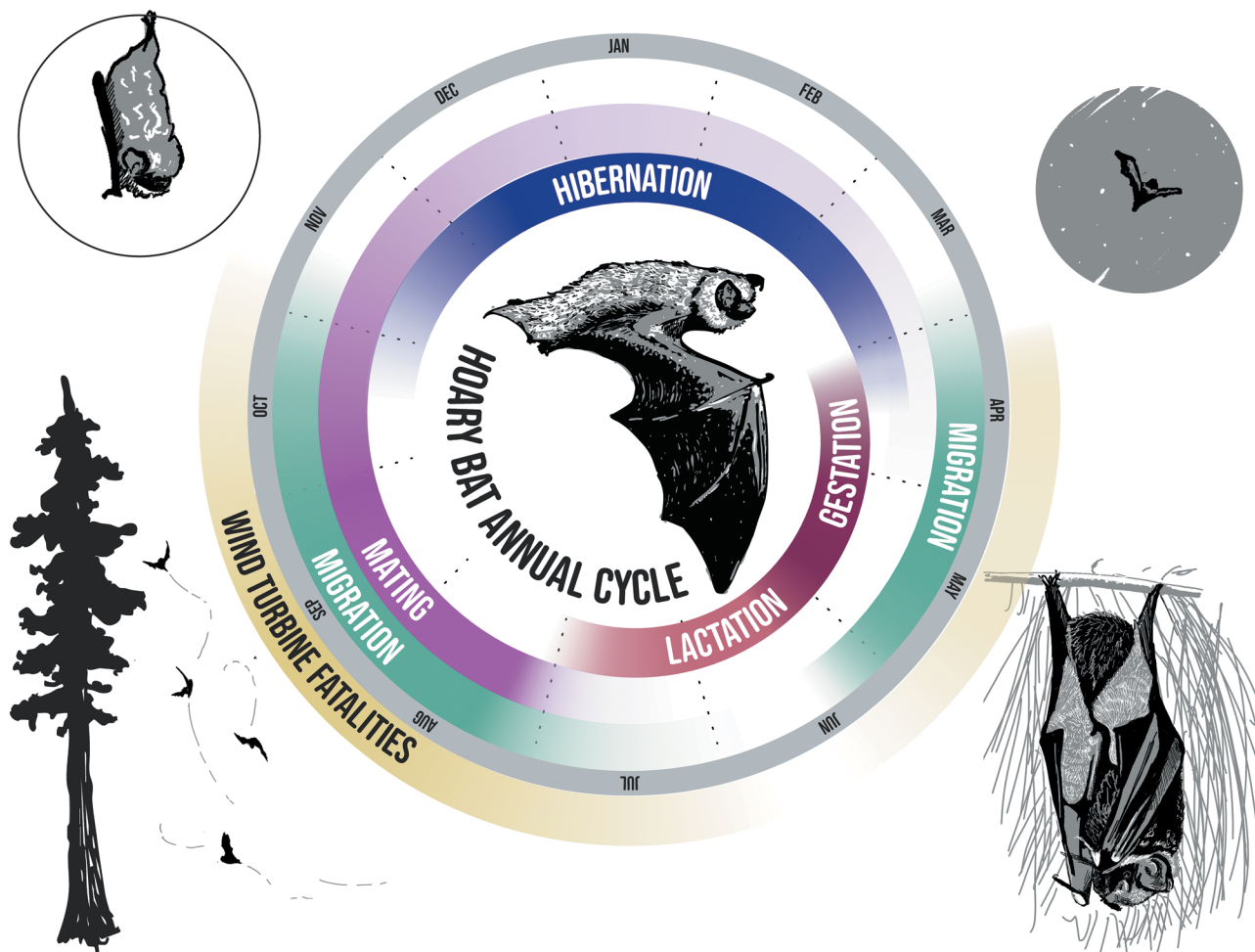


Fig. 2 Annual cycle of *Lasiurus cinereus*. Hibernation timing is estimated based on records of hibernating bats in combination with the climate of the locations in which they were observed (Weller et al. 2016; Marín et al. 2021). Timing of gestation is determined by the end of hibernation (which coincides with ovulation in many bats), early pregnancy records (Druecker 1972), and parturition (Koehler and Barclay 2000; Perry and Thill 2007; Klug et al. 2012). Timing of lactation is based on Klug et al. (2012) and spring migration based on Findley and Jones (1964), Druecker (1972), Lloyd et al. (2023), and Weaver et al. (2025a). Copulation timing is based on presence of sperm in female reproductive tracts (Cryan et al. 2012). Fall migration timing is based on fatalities at wind farms (Baerwald and Barclay 2011; Lloyd et al. 2023). Large areas of overlap and uncertainty are a product of variation by sex, life stage, and region.

(Gruver 2002; Table 1). Instead, when roost temperatures approach freezing, bats must increase their metabolic rate to avoid cellular damage from freezing tissues (Giroud et al. 2021), although the specific lower critical temperature for the species has not been documented.

Spring migration season

In spring, hoary bats transit from winter to summer habitat. At this time, fertilization occurs in females, using sperm that have been stored in the female reproductive tract through the winter. While little is known about specific timing of ovulation and fertilization or how overwintering location may influence this timing, Druecker (1972) found that ovulation peaked between late April and early May for hoary bats in New Mexico, followed by fertilization and pregnancy approximately 10 days after ovulation.

This dual challenge of gestation and migration results in females employing a time-minimization strategy during spring migration (Clerc and McGuire 2021). Although females may use torpor to delay parturition during inclement weather (Willis et al. 2006), they will

typically forgo torpor during migration to time parturition with arrival at summering grounds (Cryan and Wolf 2003). Maintaining homeothermy during migration benefits gestation but necessitates that females increase their reliance on endogenous fuel loads and ephemeral pulses of prey to accommodate the increased energetic cost associated with homeothermy (Clerc et al. 2021). Although pregnancy certainly constrains some aspects of migration, the coincidence of gestation and migration allows for early parturition dates and therefore longer growing seasons, which presumably contributes to higher offspring survival (Frick et al. 2010; Barclay 2012). Findley and Jones (1964) and Valdez and Cryan (2009) have provided some evidence that females move through New Mexico as much as a month before males, suggesting an earlier spring departure date or more northerly wintering grounds for females.

Like females, males potentially use daily torpor to optimize energy as they transition from wintering grounds to summer sites where they fatten before the mating season (Clerc and McGuire 2021). While seasonal hormonal controls that stimulate the transition to migratory physiology are well documented in birds (Deviche 1995; Tonra et al.

2011; Vandermeer 2013), the endocrine control mechanisms influencing migration in bats are not known.

Concentrated areas of Hoary Bat activity during spring have been documented in New Mexico, Arizona, and both southern and northern California (Findley and Jones 1964), which may have led in part to hypotheses that many individuals are migrating from wintering grounds in Mexico. Cryan (2003) also hypothesized that female bats may move east from wintering grounds in California; however, echolocation monitoring records from BatAMP (Bat Acoustic Monitoring Portal; <https://batamp.databasin.org>; Fig. 1) suggest that wintering grounds may be more diffuse rather than concentrated in specific areas. Most records suggest the highest spring concentrations occur in the southwest (Fig. 1), but it is unclear whether the spring population is truly concentrated in these states, or if the observed pattern is due to low survey effort in other parts of North America. Reasons for concentrated areas of occurrence are unknown but could potentially be migration stopover sites, bats becoming active near areas where they overwintered, or weather-mediated. Mating behavior may also contribute to aggregations—male bats are able to store sperm in the epididymis even outside of the typical autumn mating season (Racey 1974) and spring copulation has been observed in another bat species (Clerc et al. 2022).

Summer maternity season (females)

Female hoary bats typically give birth and raise pups between mid-May and early August (Koehler and Barclay 2000; Perry and Thill 2007; Klug et al. 2012), frequently producing 2 offspring per year (Kunz 1971; Shump and Shump 1982).

Although female hoary bats disperse widely over their summer ranges, they concentrate in the Plains region and at higher latitudes in eastern North America (Cryan 2003; Hayes et al. 2015). Museum records and predictions from species distribution models suggest that females and males overlap in the southern portion of the summer range, but females extend their summer range farther north as they occupy regions more suitable for pup rearing (Hayes et al. 2015).

Roost selection in the summer is likewise driven by pup rearing for reproductive females. While both sexes appear to prefer roosting in older, larger trees in thinned forests with less dense overstory vegetation (Perry and Thill 2007), on a finer scale, females are constrained to roosts that maximize foraging opportunities and energy savings to maximize pup survival. A study in Manitoba found most females rear young in mature deciduous and coniferous trees with sufficient surrounding vegetation that likely provides protection from wind and enhances heat and humidity retention, which would be preferential for pup rearing (Klug et al. 2012). Within these forested landscapes, lactating females also demonstrate preference for roost sites with open spaces to the south, likely to increase sun exposure and ease of exit (Constantine 1966; Willis and Brigham 2005; Klug et al. 2012).

Females are sedentary during pup rearing, and there is some evidence to suggest interannual fidelity to breeding areas, individual trees, and even locations within individual trees (Koehler and Barclay 2000; Perry and Thill 2007; Klug et al. 2012). Concentrations of lactating females have been consistently found in Cypress Hills, southwestern Saskatchewan, Canada (Willis and Brigham 2005; Green 2024) and Delta Marsh, Manitoba, Canada (Barclay 1985; Klug et al. 2012). These sites are isolated forest patches surrounded by untreed, lower elevation landscapes, creating a concentrated study site ideal for

observing the species, but this is not likely an exhaustive list of pup-rearing sites.

Summer season (males)

Less information is available regarding summer activities for male bats—we know of no life-history activities that would constrain them to be sedentary during summer (Dalquest 1943). Male hoary bats undergo spermatogenesis beginning in May (Druecker 1972), with records from a capture site in northern California demonstrating that this process can continue through autumn (T. Weller personal communication, as indicated by descended testes with no sperm stored in the caudae epididymides; Krutzsch 2000; Cryan et al. 2012).

Like females, males disperse broadly over their summer range, which includes the Rockies and higher latitudes in western North America. Additionally, given that males are not restricted by pup rearing, this sex can potentially move longer distances in summer. As an example, a male Hoary Bat in Ontario in July traveled roughly 827 km in 2 weeks, covering 253 km in a single night (Morningstar and Sandilands 2019).

Late-summer to autumn mating and migration season

Late summer through autumn, hoary bats face the dual challenge of 2 energetically expensive activities: migration and mating. The caudae epididymides in male hoary bats are often filled with sperm in late summer and early autumn, signifying sexual readiness (Druecker 1972; Racey 1979; Cryan et al. 2012; White and Umberger 2014). Furthermore, male and female Hoary Bat carcasses found at wind facilities in late summer and early autumn contained sperm, providing evidence of copulation at this time of year (Cryan et al. 2012).

As the mating season begins, individuals must locate mates across a large spatial scale. Individuals of the species are more widespread across regions and habitats in late summer and autumn than in other seasons (Hayes et al. 2015). Furthermore, evidence suggests that the late-summer and autumn movements of hoary bats are more complex and less unidirectional than exhibited in other migratory bat species (Findley and Jones 1964; Campbell et al. 2025). Adults and young of the year migrate from their respective summering habitats, sometimes in unexpected directions, before arriving at their wintering grounds (Cryan et al. 2014b; Campbell et al. 2025). Occurrence records indicate that, during this period, hoary bats generally move southward and toward both coasts of North America (Cryan 2003; Cryan et al. 2014a; Hayes et al. 2015; Wieringa et al. 2021; Campbell et al. 2025). Stable isotope data integrated from 1,513 hoary bats across several studies suggested a novel “pell-mell” migration strategy in which bats travel to both higher and lower latitudes from their summer habitats before ultimately returning to lower latitudes for winter (Campbell et al. 2025). Weller et al. (2016) documented a similar behavior in a single male Hoary Bat tagged with a GPS unit, traveling north then east during October 2014 before returning to the area in which it was tagged in northwest California. The authors cited above speculate that such complex movements are likely related to mating.

Several lines of evidence support the hypothesis that hoary bats aggregate during the autumn migration period, providing opportunities for copulation. For instance, observations of Hoary Bat arrivals and departures from Southeast Farallon Island off the coast of California over a 38-year period suggest that they aggregate there during autumn

(Cryan and Brown 2007). A known aggregation area for male hoary bats during autumn migration is in Humboldt Redwoods State Park (HRSP) in northwestern California (Salganek et al. 2022; T. Weller personal communication). HRSP contains some of the largest remaining stands of old-growth Coastal Redwood (*Sequoia sempervirens*), and hoary bats are regularly captured at this location during autumn (Weller et al. 2016), where they can be readily observed engaging in social behavior such as chasing and using atypical echolocation calls (Corcoran et al. 2021). The extreme male bias in capture rates and behavioral expression of males suggests that HRSP may be an important swarming site (Fraser and McGuire 2023; areas where females can reliably be captured during autumn are, to date, unknown).

Cryan (2008) hypothesized that hoary bats use resource defense polygyny or leks. When females are a mobile resource, males may establish temporary territories within swarming sites in regions that females are likely to visit (Cryan 2008; Jahelková and Horáček 2011). Still, it remains unclear if males use night roosts as sites to lure females into proximity or defend larger reaches of a swarming site corridor, attempting to intercept females in the open air (or alternative or combined strategies). While researchers have hypothesized that hoary bats may be attracted to the tallest trees in a landscape as potential mating or lekking sites during autumn (Cryan and Brown 2007; Cryan 2008; Cryan and Barclay 2009), this hypothesis was intended to explain potential Hoary Bat attraction to wind turbines, and the only study of roost selection by males in autumn does not support the tallest-tree hypothesis (Salganek et al. 2022).

Few studies exist of roost site selection during autumn (see Table 1 for a summary of these studies), and there are no published records of female autumn roosting behavior. Salganek et al. (2022) located 24 roosts for 16 different male hoary bats in California in autumn, suggesting preference for roost sites near creeks, roads, and meadows. The authors concluded that the road-creek corridor created a wide, somewhat linear, open space through the forest that is consistent with what is known about flyways used by hoary bats (Loeb and O'Keefe 2011).

Although hoary bats are high-intensity echolocators, Corcoran and Weller (2018) found that during autumn, male hoary bats produce low-intensity echolocation calls, which they termed “micro calls,” and sometimes fly without echolocating. Hoary Bat micro calls are relatively high-frequency (~53 kHz), short-duration (~0.5 ms) calls; thus, they would not be recognized as Hoary Bat calls by most automated identification software using typical settings. Use of micro calls may allow males to reduce eavesdropping by conspecifics during mate-seeking while still allowing them to avoid collision with large objects (Corcoran et al. 2021). It is unclear if female hoary bats also use reduced forms of echolocation or if males employ this strategy at other times of year. The lower reaction time afforded by micro calls, paired with a potential increased use of social calls, could contribute to the relatively high wind turbine collision rates for the species.

Wind energy development as a seasonal threat

Since the mid-2000s, wind energy and white nose syndrome (WNS) have been the leading causes of documented mass mortality events for bats in North America (O'Shea et al. 2016), although WNS is not known to impact hoary bats (Alves et al. 2014). Climate and land-use change interact to create additional threats to bats including loss of insect prey and roost sites (Fig. 3; Frick et al. 2020; Adams et al. 2024). Management for many threats could be addressed through seasonal practices such as mindful application of forest management actions at known roost sites during winter when hoary bats employ torpor

and may not be capable of reacting to disturbance. Other threats require a more nuanced approach—impacts of toxins, for example, would need to be addressed more generally wherever females are consuming insects and accumulating toxins, across multiple seasons. While other threats are likely to impact the population (see COSEWIC 2023; Adams et al. 2024; Fig. 3 for further explanation of these threats), direct impacts from wind turbines are widely recognized as the leading known threat to hoary bats. Regardless, the efficacy of managing any of these other threats is unknown relative to addressing wind energy generation, where effective mitigation of the mortality from wind turbines has been demonstrated. Likewise, the seasonal concentration of Hoary Bat fatalities at wind energy facilities in autumn makes this challenge more tractable.

Defining the problem

While energy development may indirectly affect bats through habitat conversion (Ellerbrok et al. 2022, 2024), the primary concern is that bats are killed by rotating wind turbine blades (Grodsky et al. 2011; Rollins et al. 2012; Lawson et al. 2020). Hoary bats make up approximately 30% of all bat fatalities observed at wind energy facilities across the United States and Canada, and Hoary Bat carcasses have been documented at nearly all facilities that have conducted post-construction fatality monitoring (Arnett and Baerwald 2013; Zimmerling and Francis 2016; REWI 2026). Moreover, at most sites hoary bats make up a disproportionate number of fatalities compared to their relative abundance as determined via capture and acoustic detection (Gruver 2002).

Cumulative effects

Overall impacts of wind turbines and other threats to the Hoary Bat population are challenging to assess because reliable estimates of population size and growth rate are lacking. An analysis of post-construction fatality studies across 48 wind energy facilities in southern Ontario from 2010 to 2017 suggested a 16% reduction in the Hoary Bat population over the 8 yr period, after accounting for the effects of curtailment (Davy et al. 2021). Studies based on summer acoustic and capture surveys show mixed results. Udel et al. (2025) reported a 24% decline in the relative abundance of hoary bats based on data from a continental-scale dataset from the North American Bat Monitoring Program (NABat, 2012 to 2023). However, a study in Canada that looked at local abundances of hoary bats across 20 years using summer mist netting surveys did not observe an obvious decline (Green et al. 2021).

Frick et al. (2017) used a range of plausible demographic scenarios based on the most conservative data from similar species and expert assessment to model how wind energy facilities could influence Hoary Bat population trajectories. Results showed that under certain conditions, 2014 levels of collision mortality could cause severe population decline within 50 years and increased extinction risk within 100 years (Frick et al. 2017). Also, 75% of expert assessments estimated a Hoary Bat population size that would result in a 90% population decline within 50 years, and even outcomes based on the highest expert-elicited estimations of Hoary Bat population size showed that the modeled population growth rate would need to increase to compensate for mortality at wind energy facilities. Friedenber and Frick (2021) built on this work to account for the build-out of wind energy facilities in North America anticipated by 2050. Models indicated that even the high population growth rates that were projected to allow population viability under the assumptions modeled in 2017 were

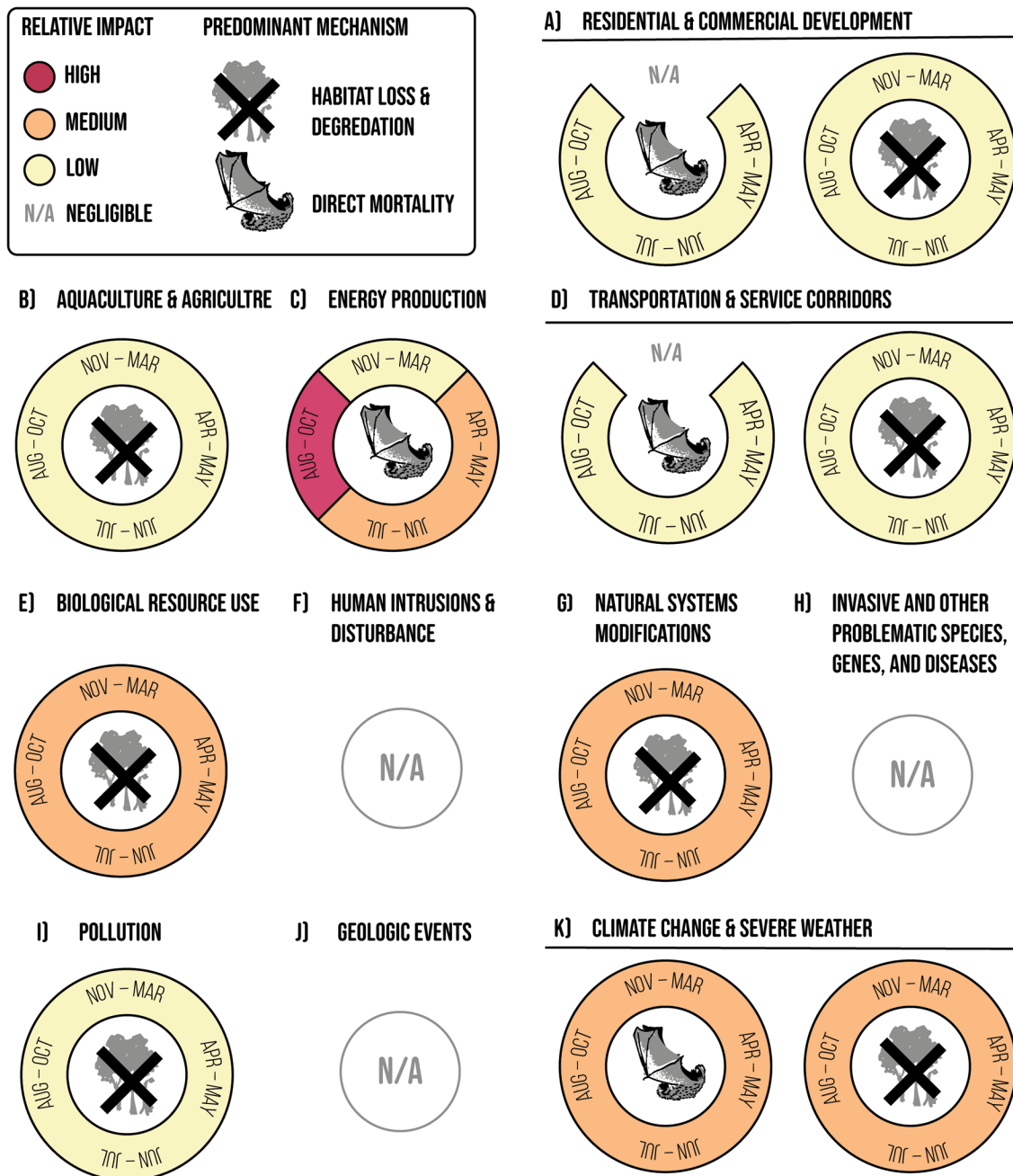


Fig. 3 Relative impact of threats to hoary bats by time of year. Threats are defined by the Level 1 Standardized IUCN Threats Classification Schema (Salafsky et al. 2025). Relative impacts for each threat are derived from the expert elicitation as provided by Adams et al. (2024) and this literature review. Colors indicate relative potential threat impact by season, though timing is approximate and can vary depending on the region. Habitat loss or degradation includes loss of roosting or foraging habitat as well as loss of insect prey (Fenton 1997; Cardoso et al. 2020; Gebremariam 2024). Direct mortality was considered “negligible” for some threats during winter months because hibernation behavior reduces exposure of bats to these threats. Threats (Adams et al. 2024) were assigned medium or high relative threat levels. Threats assigned a low relative threat level have been identified in the literature as either being a source of direct mortality for hoary bats or contributing to insect declines. IUCN threats without this level of support in the literature are assigned a negligible relative threat level (as indicated by “NA”). Additional known contributing factors and literature sources for Level 1 relative impact are provided below: (A) impalement by barbed wire associated with commercial development (Iwen 1958); (B) habitat conversion, pesticide use, and grazing contributing to loss of insect diversity and abundance, water resources, and available roosts (Rolseth et al. 1994; Rambo and Faeth 1999; Krueess and Tscharrntke 2002; Zedler and Kercher 2005; Sánchez-Bayo et al. 2016; Sánchez-Bayo and Wyckhuys 2019); (C) experts from Canada, Mexico, and the US identified renewable energy as the leading threat to hoary bats due to collisions with wind energy turbines (Adams et al. 2024) with seasonality determined by Arnett et al. (2008), Baerwald and Barclay (2011), and Lloyd et al. (2023); (D) flight paths were the third-ranked mortality source in Canada (Adams et al. 2024) with seasonality informed by Peurach et al. (2009); (E) logging and wood harvesting were the second-ranked threat in Canada (Adams et al. 2024); (F) NA; (G) fire and fire suppression were the third-ranked threat in the United States (Adams et al. 2024); (H) predation by cats (Szentivanyi et al. 2024); (I) degradation of habitat from water, noise, and light pollution (Clark and Lamont 1976; Reidinger 1976; Pybus et al. 1986; Michalak et al. 2013; Morrissey et al. 2015; Hsiao et al. 2016; Sánchez-Bayo et al. 2016; Braak et al. 2018; Wu et al. 2020; Quandahor et al. 2024; Valdespino et al. 2024); (J) NA. (K) Drought was the second-ranked threat in the United States and Mexico, and temperature extremes were the third-ranked threat in the United States (Adams et al. 2024). Threat impact scores do not necessarily correspond to standardized threat assessment scoring used by IUCN or NatureServe and are presented for assessment of “relative” impact of threats by season and the mechanism for each, whether habitat loss or direct mortality.

projected to lead to a risk of decline and extinction in under 40 years once wind energy facility build-out was considered. Outcomes based on the lowest-risk scenario for a mid-level population size projected that Hoary Bat populations would experience a 50% decrease by 2028, although adding mitigation practices to the model lowered the projected impact of build-out. Overall, these models indicate that fatalities of hoary bats at wind turbines could already be driving population decline and that widespread adoption of fatality minimization measures across their range may be needed to manage the risk of population decline. However, these models also highlight the lack of basic information about the current population size and status of the species.

Spatio-temporal patterns in wind turbine fatalities

Hoary Bat fatalities peak from early to mid-July through September, when young of the year are volant and migration and mating are underway (Lloyd et al. 2023; Labuzzetta et al. 2026). This fatality peak tends to occur earlier at higher latitudes (Lloyd et al. 2023), consistent with a wave of migratory arrivals at wind energy facilities. During this period of high risk, higher fatality rates for hoary bats are associated with lower wind speed and other weather patterns such as the passage of storm fronts (Arnett et al. 2008) and warmer temperatures (Labuzzetta et al. 2026).

Overall recorded bat fatalities at wind energy facilities are much lower during the spring migratory period than in the autumn (Arnett et al. 2008; Thompson et al. 2017; Lloyd et al. 2023), indicating that migratory movement alone is insufficient to explain collision risk and that behaviors associated with autumn movement specifically may be a contributing factor. A slight uptick in Hoary Bat fatalities has been documented in May and June in the Ozark/Appalachian Forest region (Lloyd et al. 2023), but in general, there is more uncertainty about spring mortality because monitoring efforts during this season are conducted less often than in summer and autumn (Arnett et al. 2008; Lloyd et al. 2023). Risk also varies between sexes, depending on the specific timing and facility location, suggesting that sex-specific seasonal needs also influence collision risk. Female hoary bats at a wind energy site in Indiana demonstrated a higher collision risk in early to mid-May, when they would be moving toward maternity sites, and in August, when females would be seeking mating opportunities and moving toward over-wintering sites (Weaver et al. 2025a). The same study suggested a higher risk to males from mid-September to mid-October (although this difference was not statistically significant at any individual site; Weaver et al. 2025a). Hoary Bat exposure to wind turbines could be greater in autumn than spring if movement routes are more circuitous, which is likely given that autumnal movements serve the dual purpose of migration and mating, especially for males. During spring, seasonal movements may be more focused and directional for both males and females, reducing exposure relative to late summer and autumn, but this remains to be demonstrated.

Isotope analyses of carcasses found underneath wind turbines show that bats killed at a given wind energy facility are likely a mixture of migrants and bats of local origin (Baerwald et al. 2014; Pylant et al. 2016). Furthermore, a recent study that combined isotope analyses with trace element data and species distribution models found that, for hoary bats killed at wind energy facilities, the ratio of individuals that had recently migrated vs those that had spent summers locally varied by season and year between sites (Wieringa et al. 2024). Campbell et al. (2025) included bat carcasses from a broader spatial coverage to further confirm what these previous studies had

indicated: wind energy facilities typically have a large geographic catchment area for hoary bats.

Behaviors increasing collision risk

Research suggests that Hoary Bat presence or absence at a wind energy facility prior to construction is a poor predictor of post-construction fatality rates at that facility (Cryan and Barclay 2009; Solick et al. 2020). This pattern may suggest that wind energy infrastructure serves as an attractant for some species of bats (Guest et al. 2022; Jonasson et al. 2024). Exact behavioral causes for the relatively high risk of wind turbine collision remain unknown and this continues to be an active area of research.

Cryan et al. (2014a) documented frequent calls of high-flying bats that did not interact with the rotor-swept zone, and Aghababian (2023) observed aerial targets flying linearly above rotor-swept zones and nonlinearly at lower heights. Thus, bats may not be particularly exposed to wind energy infrastructure during long-distance migratory flights, but rather when they are foraging, exploring, chasing, roosting, and/or exhibiting social behaviors near wind turbines during autumn (e.g., Cryan et al. 2012, 2014a; Rydell et al. 2016; Bennett et al. 2017; Foo et al. 2017; Goldenberg et al. 2021; Nagy et al. 2026). For example, reduced use of echolocation in social situations at night during autumn (Corcoran et al. 2021) could contribute to proximate causes of mortality at wind energy facilities by limiting navigational cues that would aid in avoiding moving turbine blades.

Observations of bat activity via thermal cameras pointed toward the nacelle (i.e., hub) have documented that bats often approach turbines from the leeward side and are less likely to approach operating turbines as wind speeds increase, although these observations were not species-specific (Cryan et al. 2014a; Schirmacher 2020; Aghababian 2023). Three-dimensional thermal videos with broader viewsheds have revealed that bat activity can be 3 times higher in the lower half of the rotor-swept zone than the upper half (Aghababian 2023; Weaver et al. 2025b), and that bat density can be higher in the rotor-swept zone than in the free airspace around wind turbines (Nagy et al. 2026). Consistent with these observations for bats as a group, Garvin et al. (2024) observed Hoary Bat fatalities to be negatively correlated with the minimum rotor height above ground level (i.e., ground clearance), indicating that Hoary Bat collisions with wind turbines tend to occur when bats are flying at lower altitudes, regardless of turbine dimensions. Nonetheless, other research has indicated that different turbine dimensions are associated with higher fatality rates. Barclay et al. (2007) found higher bat mortality at wind energy facilities with higher hub heights, regardless of nameplate capacity (a proxy for rotor diameter). However, Barclay et al. (2007) did not assess this relationship by species. While Labuzzetta et al. (2026) found no relationship between Hoary Bat mortality and ground clearance, they did observe an increase with larger rotor-swept area; however, there was little variation in wind turbine designs in their study of 19 wind energy facilities in Iowa, United States compared with the broader geographic assessment by Garvin et al. (2024).

Minimizing wind turbine collision risk

Turbine blades can reach exceptional speeds, especially at the blade tips (e.g., 80 m/s at the tip for a 5-MW wind turbine with 62.6-m-long blades; Jonkman et al. 2009). Because the drivers of risk are not well understood, minimization measures generally focus on deterrence and curtailment (USFWS 2012, 2024b; American Clean Power [ACP] 2015; Pruitt et al. 2016; Whithy et al. 2021). Although, as mentioned above, increasing the distance between the ground and the minimum

rotor sweep may also aid in reducing collision risk for hoary bats (Garvin et al. 2024).

Ultrasonic stimuli have been deployed to deter bats, in theory by disrupting their ability to receive and interpret their own echolocation (Arnett et al. 2013). Studies have primarily positioned devices on the nacelle of wind turbines and used frequencies ranging between 20 and 50 kHz. The efficacy of ultrasonic deterrents varies widely by location and species, with reported results spanning from decreased, similar, or even increased fatalities (Arnett et al. 2013; Romano et al. 2019; Schirmacher 2020; Weaver et al. 2020; Clerc et al. 2025). It remains unclear why ultrasonic deterrent effectiveness varies among species, but it may relate to the number and placement of acoustic deterrents on wind turbines, the acoustic signal that is emitted (e.g., constant broadband noise or frequency sweeps), or how bats respond to the emitted ultrasound. The physics of sound likely plays an important role in the effectiveness of ultrasonic deterrents. Sound rapidly attenuates at higher frequencies; thus, bats may not receive the signal until they are already near the rotating blades. It may be possible to improve ultrasonic technologies by investigating how bats respond to different stimuli. Fritts et al. (2024) reported that both low and high-frequency calling bats flew farther from deterrent treatments that included relatively low ultrasonic frequencies (20 to 32 kHz). Focusing sound within this range may be beneficial going forward given that lower frequencies travel farther and cover more area than higher frequencies. Another potential means of improving the effectiveness of ultrasonic deterrents is to place them closer to the ground or on the turbine blades.

Visual strategies to reduce collisions by increasing turbine visibility have also been investigated (e.g., Gorresen et al. 2015a, 2015b), but many of these studies have been preliminary. Cryan et al. (2022) pilot-tested dim-flickering ultraviolet light broadcast onto turbine surfaces to increase turbine visibility but did not find evidence that it reduced bat activity around the turbine. Visual strategies may be able to influence bat behavior at a greater distance from turbines than acoustic deterrents; therefore, such strategies might warrant further investigation (Guest et al. 2022; Jonasson et al. 2024, 2025).

The most effective minimization strategy to reduce bat fatalities at wind turbines involves slowing the rotational speed of wind turbines during conditions when bats are at risk, often referred to as curtailment, and preventing the wind turbines from rotating below cut-in speed (i.e., the wind speed at which turbines begin producing energy, typically 3.0 m/s). In contrast to many species of birds, bats demonstrate little risk of collision with wind turbines when the rotors are immobile (Smallwood and Bell 2020). A review of 10 post-construction monitoring studies found that curtailing wind turbines below wind speeds of 5.0 to 6.0 m/s reduced fatalities across bat species by 63% (Adams et al. 2021). A meta-analysis of 20 control-treatment comparisons across 7 wind facilities in the United States and Canada, with curtailment speeds ranging from 3.5 to 6.5 m/s, suggested that every 1 m/s increase in cut-in speed could reduce Hoary Bat fatalities by 28% (95% CI: 0.4% to 48%) on average, with an average 48% (95% CI: 24% to 64%) reduction in Hoary Bat fatalities observed at facilities employing a 5 m/s cut-in speed (Whitby et al. 2024). The curtailment strategies included in these meta-analyses are referred to as “blanket curtailment” because a single raised cut-in speed was implemented all night long during the late summer and early autumn (USFWS 2024b).

Even within this high-risk season of late summer and early autumn, bat activity varies with wind speed, moon illumination, rainfall, temperature, and other weather variables, as well as with insect availability and time of night and season (e.g., Weller and Baldwin

2012; Gorman et al. 2021; Maynard et al. 2023). Therefore, considerable effort has been expended to develop “informed” or “smart curtailment” strategies that use bat activity and other variables to determine when bats will be at greatest risk of collision at a given wind energy facility. These curtailment strategies are often intended to reduce the loss of energy production while retaining bat fatality reductions expected with blanket curtailment (e.g., Barré et al. 2023) and typically fall into 1 of 2 categories (USFWS 2024b): (i) activity-based (or algorithm-based) informed curtailment (ABIC), which uses predictive modeling to curtail turbines when bats are expected to be present (e.g., Barré et al. 2023; Gottlieb et al. 2024; Peterson et al. 2025); and (ii) real-time presence-informed curtailment (RTPIC), which uses surveillance technology, e.g., acoustic detectors (i.e., real-time acoustic-activated smart curtailment), thermal video cameras, and radar to activate curtailment when bats are detected (e.g., Hayes et al. 2019; Vallejo et al. 2023; Newman et al. 2024).

Potential costs of curtailment to wind energy production vary across studies. One study that modeled lost wind energy production across Ontario, Canada, under a blanket curtailment scenario in which all wind turbines were curtailed at wind speeds below 5.5 m/s from 6 p.m. to 6 a.m. during 15 July to 30 September 2020 estimated a 0.48% loss in energy production—equivalent to 6.79 ± 0.9 million CAD earnings loss compared to estimated net earnings of 1.6 ± 0.21 billion CAD (Thurber et al. 2023). By contrast, MacLaurin et al. (2022) found that blanket curtailment at or above 6.9 m/s could make some wind energy projects financially infeasible, especially in regions with high wind resource variability. Conversely, curtailing at 5.0 m/s reduced profitability of wind energy by 2.9% nationally (vs a 26% reduction for the 6.9 m/s curtailment scenario; MacLaurin et al. 2022). A simulation study, using data from Alberta, Canada, showed that ABIC would reduce energy production loss by 50% to 100% compared with blanket curtailment and that the value of ABIC depended on bat activity levels and nighttime wind speeds (Hayes et al. 2023). Cost savings of ABIC over blanket curtailment are also likely to be more pronounced when curtailment is imposed at wind speeds higher than 5.0 m/s (Peterson et al. 2025). Conversely, an RTPIC system appeared to demonstrate better cost savings when implemented at lower wind speeds (5.0 vs. 6.9 m/s) compared to blanket curtailment at the same wind speeds (Vallejo et al. 2023). Rabie et al. (2022) found no cost savings of RTPIC over blanket curtailment, but the study used different cut-in speeds for each (8.0 m/s vs 4.5 m/s, respectively). Continued efforts are needed to advance and improve smart curtailment strategies that balance Hoary Bat collision risk reduction with energy generation potential.

Knowledge gaps and management implications

Wind energy is the largest identified driver of mortality for hoary bats, and the current state of research highlights autumn as a critical portion of the annual cycle to address this risk (Fig. 3). Autumn for hoary bats is characterized by mating and migration from summer to winter habitat, both of which involve broad-scale movements across the landscape—an activity that is inherently risky, made riskier by a growing number of wind turbines on the landscape. The seasonality of wind energy impacts to hoary bats, as well as the ability to document fatalities resulting from wind energy facilities, creates a logical pathway for implementing management strategies focused on turbine collision reduction. Additionally, the differences in life history strategies between sexes suggest a need to better understand sex-specific population vital rates, collision rates, and behavioral

causes of risk. Research focused on key knowledge gaps could allow for more informed decisions to manage this conflict.

The most important (and elusive) questions have been those related to population-level impacts. Empirical assessment of population size and demographic rates has not yet been possible for these elusive bats (Lentini et al. 2015; Frick et al. 2017). A lack of empirical data is common for bats in general and for migratory bats in particular due to their cryptic nature, and this knowledge gap poses a challenge to understanding how anthropogenic stressors impact population stability (Diffendorfer et al. 2015; Frick et al. 2017). Current understanding of Hoary Bat population status is based on models that incorporate uncertainty about population size and demographic factors to predict the trajectory of Hoary Bat populations over time (Frick et al. 2017; Friedenberg and Frick 2021). These models have also used data from similar species and expert elicitation to establish a range of plausible population sizes and demographic measurements to predict how risk factors could impact Hoary Bat populations under various scenarios (Frick et al. 2017; Friedenberg and Frick 2021). This strategy of using data from similar species or expert assessments is frequently applied for conservation purposes when empirical data are unavailable (Burgman et al. 2001; Martin et al. 2012; Drescher et al. 2013). In some cases, such assumptions can create misleading results if true vital rates are not comparable. Refining sex-specific survival estimates for adults and young of the year, as well as baseline population size, can provide a clearer picture of the level of risk posed by wind turbines and other stressors.

Monitoring data, collected systematically, can be used to check the validity of population projection modeling by detecting trends in Hoary Bat occupancy and abundance over time (Rodhouse et al. 2019; Reichert et al. 2021). Long-term acoustic and genetic data can provide insight into Hoary Bat occupancy and effective population size, respectively (Hale et al. 2022), as well as sex differences in fatality rates (Weaver et al. 2025a). Several studies have attempted to use genetic analysis to estimate effective population size or changes in the breeding population size over evolutionary time scales, but results so far have been inconclusive (Korstian et al. 2015; Cornman et al. 2021) or inconsistent (Pylant et al. 2016; Sovic et al. 2016). While Hoary Bat occurrence records are available via NABat and BatAMP acoustic databases, there remains a paucity of data in the United States Great Plains (see Fig. 1) where wind energy projects are heavily concentrated (Hoen et al. 2018). While many of these projects likely have acoustic records for bats, based on guidance for wind energy development (USFWS 2012), few of these data are publicly available in the NABat or BatAMP repositories.

Fatality surveys at wind energy facilities, often referred to as post-construction mortality monitoring, can also be used to refine Hoary Bat population projections. These measures have been used as proxies for population indexes for hoary bats, similar to roadkill surveys in terrestrial mammals (e.g., Jahn 1959; Rolley and Lehman 1992). Doing so, however, requires validation that the available data are representative samples of the population (Baker et al. 2004). Alternatively, fatality survey data at a subset of wind energy facilities can be used to estimate cumulative wind turbine mortality if monitoring is conducted in ways that provide sufficient statistical rigor (Huso and Dalthorp 2014). Additionally, range-wide analyses of robust wind turbine fatality survey data can provide correlative insights to potential environmental drivers of collision risk. However, to date, the projects that report fatality data are not necessarily a representative sample of projects across the range of the species. The high variation in the number of fatalities across facilities and regions, the current

opportunistic nature of fatality surveys nationally, and little information on the stochastic drivers of fatality events make it challenging to estimate the cumulative take of hoary bats from wind energy development.

Whether acoustic, genetic, or fatality survey, each data source would produce more useful, robust results if collected via a question-driven, rigorously designed sampling regime over the species' range. A data-driven understanding of cumulative population-level impacts to hoary bats from wind turbine fatalities will benefit greatly from better coordination of data collection and sharing, including sharing acoustic and fatality data as well as bat tissue samples from fatality surveys across wind energy facilities, which can form the basis of a genetic repository.

On a finer scale, questions remain regarding the behaviors and sensory cues (Jonasson et al. 2024) that might contribute to wind turbine collision risk for male, female, and juvenile hoary bats. While there is evidence that hoary bats may be attracted to wind turbines (Guest et al. 2022; Jonasson et al. 2024), we do not know the reason why or from what distance this potential attraction may be relevant, which part of the wind turbine may be most attractive, or how sex and age may influence this. Such knowledge gaps limit our ability to develop collision avoidance and minimization strategies that target the specific drivers of collision risk for hoary bats. Jonasson et al. (2025) flew hoary bats through a Y-maze and found that bats were nearly 3 times more likely to approach dimly lit turbine surfaces than to choose dark, open exits. This pattern suggests that vision may underly bat attraction to wind turbines at close distances. Additional in situ and ex situ behavioral studies to test the leading attraction hypotheses may help inform future risk minimization strategies (Guest et al. 2022).

While we have enough occurrence records to define the seasonal range for the species (at least in the United States and Canada; Hayes et al. 2015), we have little information about how hoary bats move across the landscape and how these movements might influence turbine collision risk. Assessment of dynamic movements during transition between mating and overwintering habitat, often in remote areas, will require improvements in new technologies (Marra et al. 2015). Expansion in the use of the Motus network to track movements of bats is likely to provide insights into long-distance movements (Morningstar and Sandilands 2019). Additionally, stable isotope analyses (Vander Zanden et al. 2018; Campbell et al. 2025) and advances in GPS tracking technologies (Castle et al. 2015; Weller et al. 2016) promise to improve our understanding of intra- and inter-seasonal movements by hoary bats.

Beyond challenges with wind energy production, as noted earlier, we have little information regarding the level of impact other threats have on Hoary Bat population stability. While addressing wind turbine collision risk currently provides the most obvious path to conservation actions for the species, better understanding of other conservation challenges provides an opportunity to offset take from wind energy development that cannot be entirely avoided or minimized. For example, detailed information on movements and potential hotspots throughout the annual cycle (e.g., mating, stopover, wintering, and pup rearing) as described above could potentially illuminate areas for habitat conservation.

While an abundance of questions remains regarding the ecology of hoary bats and how that informs approaches for conservation, it is important to also highlight the value of the information available with which to make impactful management decisions (Runge et al. 2014). Delaying decisions until additional research becomes available could

allow populations to significantly diminish, ultimately raising the cost for population recovery. Fortunately, processes exist for making decisions in contexts where multiple objectives, scientific uncertainty, and conflicting values meet the reality of important species management needs. Structured decision-making is 1 such process (Runge 2011) and has been used to facilitate bat conservation management previously in the context of WNS to define specific objectives around WNS management, identify potential actions to manage WNS, and evaluate the likelihood of each outcome under each action given the current state of knowledge (Szymanski et al. 2009). Structured decision-making can also illuminate which information gaps are most critical in forecasting the performance of each action (Moore and Runge 2012). Effective minimization options (i.e., curtailment) exist that can be implemented now to improve Hoary Bat conservation based on current knowledge while using a decision analysis to pinpoint which of the research questions explored above are most critical to inform future decision-making.

Given the interaction between hoary bats and wind energy production during autumn, this season of mating and migration distinguishes itself as a clear opportunity to implement conservation action for the species. Species that engage in erratic or nomadic movements across the landscape, as the Hoary Bat does, are among the most difficult to conserve (Runge et al. 2014). Previous work calling out the need for conservation action across the annual cycle (as in the case with waterfowl) has focused on actions within breeding and overwintering habitat (Davis et al. 2025), but few have addressed transitional/migration habitat between them (Runge et al. 2015). Thoughtful and deliberate decision-making that considers this critical transitional period in the annual cycle of hoary bats could have lasting implications for the viability of this and other bat species.

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Perspective